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A Comparative Study of Nanofluids for Tuneable Filter Operation

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Abstract-Nanofluids are engineered colloidal suspensions of nanoparticles in a base fluid[1]. The nanoparticles used in nanofluids are typically made of metals, oxides, carbides, or carbon nanotubes. Common base fluids include water, ethylene glycol [2] and oil. Recent reports have revealed the possibility of developing fluid filters deviating from the conventional modelling and design techniques. Mixtures of nanoparticles in liquids can be used as an alternative to conventional optical filters [3]. In this paper the optical transmittance spectrum of hematite, silicon, gadolinium and titanium nitride with the variation of volume fraction, thickness of liquid layer and particle diameter will be analysed using simulation results for the determination of feasibility of their use in tuneable optical filter operation.

Keywords-Nanoparticles, basefluid, nanofluid, transmittance, tunable optical filter.

I. Introduction

The first decade of nanofluid research was primarily focused on measuring and modelling fundamental thermo physical properties of nanofluids (thermal conductivity, density, viscosity, heat transfer coefficient).Early research on nanofluid filters were associated with solar energy harvesting. The appropriate liquid-filter material must meet several requirements, including adequate refractive index and absorption coefficients, optical constants that determine a satisfactory spectral response, solubility and stability in cold and hot water, and environmental safety. An ideal optical limiter should be transparent to low energy laser pulses and opaque at high energies, so that it can protect human eyes and optical sensors from intense laser radiation [4]. This paper compares the response of four different types of nanoparticles namely hematite, silicon, gadolinium and titanium nitride in water (which acts as the basefluid here) to different wavelengths. The analysis is based on simulation results only which do not account for temperature effects and external magnetic and electric fields.

II. Mathematical Model

Mie theory was used to calculate the scattering and extinction efficiency[5] factors of a single homogeneous sphere particle. In this study the relative refractive index was applied because the nanoparticle was immersed in the base fluid. The relative refractive index is defined as:

$$m=\frac{n_p+ik_p}{n_m} \qquad \text{eq-1}$$

where n_p and κ_p are the real and imaginary parts of the complex refractive index of the nanoparticle, respectively, and n_m is the refractive index of the dispersed medium. The size parameter is defined by equation (2) where **d** is the diameter of the nanoparticle and **λ** is the wavelength in the medium.

$$\chi = \frac{\pi d}{\lambda} \qquad \text{eq-2}$$

The extinction efficiency factor of the nanoparticle can be calculated by:

$$Q_{e,\lambda} = \frac{2}{\chi^2}\sum_{n=1}^{\infty}(2n+1)Re(\ a_n + b_n) \qquad \text{eq-3}$$

where $\mathbf{a_n}$ and $\mathbf{b_n}$ are Mie scattering coefficients, which can be found by solving Bessel functions. The determination of the extinction coefficient for a non-absorbing monodisperse particulate medium where f_v is the volume fraction of nanoparticles is given by equation (4). If absorbing of the base fluid (water) is taken into account, the extinction coefficient for the water-based nanofluid is given by equation (5) where κ_{bf} is the extinction coefficient of the base fluid.

$$K_{e,\lambda} = \frac{1.5}{d} f_v Q_{e,\lambda} \qquad \text{eq-4}$$

$$K_{e,\lambda} = \frac{1.5}{d} f_v Q_{e,\lambda} + \ (1 - f_v)\ \frac{4\pi\kappa_{bf}}{\lambda} \qquad \text{eq-5}$$

$$T = \frac{I}{I_0} = e^{(-}K_{e,\lambda}, l) \qquad \text{eq-6}$$

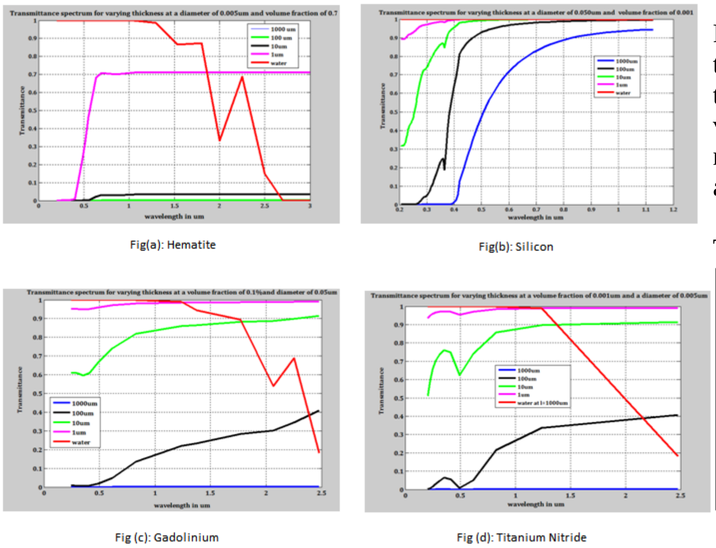
The regular transmittance of a liquid layer with a thickness of l µm can be determined by Beer's law using equation (6).

III. Results and Tables

The following section analyses the transmittance spectrum for the different types of nanofluids considered and compares them on the basis of the range of transmission wavelengths, the linearity of the graphs and also the controlling parameters such as particle size, volume fraction and the thickness of the fluid layer. The chart given below is the key to interpreting the information in the following tables.

Linearity	Linearly increasing	Linearly decreasing	Linearly constant	Non-Linearly increasing
Symbol	LI	LD	LC	NI

A. Transmittance for varying nanofluid layer thickness



Fig(a): Hematite
Fig(b): Silicon
Fig (c): Gadolinium
Fig (d): Titanium Nitride

Fig1: Showing the effect of varying thickness on transmittance for a. Hematite b. Silicon c. Gadolinium and d. Titanium Nitride.

The transmittance patterns of Fig: 1 is better explained by the following tables associated with specific thicknesses.

According to Table 1 the best transmittance for wavelengths below 0.5 µm is offered by Gd and for the rest of the wavelengths Si dominates over all the other nanofluids under consideration by having a 100% transmittance. It can also be seen that the volume fraction of the nano particle in the base fluid and the particle size at which these targets can be reached are realizable figures. Since, these simulations do not take into account reflections at the boundary of the enclosure of the nanofluid, practical values of the transmittance in the mentioned ranges might differ slightly. Heamtite has the lowest transmittance compared to the rest of the nanofluids for all the specified wavelengths.

Table 1

Nanofluid	Percentage Transmittance at different wavelengths at a fluid layer Thickness of 1um Wavelength (um)				Volume Fraction (%)	Diameter in (um)	Linearity			
	0-0.5	0.5-1.0	1.0-1.5	1.5-2.0			0-0.5 um	0.5-1 um	1-1.5 um	1.5-2 um
Hematite	0-30 %	30-70%	72%	72%	70	0.005	LI	LI	LC	LC
Silicon	90-100%	100%	100%	100%	0.1	0.05	LI	LC	LC	LC
Gadolinium	95-98%	99%	99%	99%	0.1	0.05	LI	LC	LC	LC
Titanium Nitride	92-95%	95-99%	99%	99%	0.1	0.005	LI	LI	LC	LC

Table 2

Nanofluid	Percentage Transmittance at different wavelengths at a fluid layer Thickness of 10 um Wavelength (um)				Volume Fraction (%)	Diameter in (um)	Linearity			
	0-0.5	0.5-1.0	1.0-1.5	1.5-2.0			0-0.5 um	0.5-1 um	1-1.5 um	1.5-2 um
Hematite	0%	0-2%	2%	2%	70	0.005	LC	LI	LC	LC
Silicon	30-100%	100%	100%	100%	0.1	0.05	LI	LC	LC	LC
Gadolinium	60-70%	70-83%	83-88%	88-89%	0.1	0.05	LI	LI	LI	LI
Titanium Nitride	50-62	62-89%	89-90%	90%	0.1	0.005	NI	LI	LI	LC

From Table 2 it can be seen that once again the overall results for transmittance in all the wavelength ranges are good for Si even though the level of transmittance has degraded compared to the values obtained at a lower thickness than 10µm. Hematite nanofluid shows the most resistance to optical transmittance for all the ranges peaking at a highest of 2%.

Table 3

Nanofluid	Percentage Transmittance at different wavelengths at a fluid layer Thickness of 100 um Wavelength (um)				Volume Fraction (%)	Diameter in (um)	Linearity			
	0-0.5	0.5-1.0	1.0-1.5	1.5-2.0			0-0.5 um	0.5-1 um	1-1.5 um	1.5-2 um
Hematite	0%	0%	0%	0%	70	0.005	LC	LC	LC	LC
Silicon	0-92%	92-100%	100%	100%	0.1	0.05	LI	LI	LC	LC
Gadolinium	0-1%	1-18%	18-25%	25-30%	0.1	0.05	LI	LI	LI	LI
Titanium Nitride	0-3%	0-29%	29-35%	35-39%	0.1	0.005	NI	LI	LI	LI

Most practical conventional thin film filters have a thickness in the order of 100µm. Therefore, as a comparison the best performance for transmittance in this range of thickness is offered by Si as opposed to hematite.

Table 4

Nanofluid	Percentage Transmittance at different wavelengths at a fluid layer Thickness of 1000um Wavelength (um)				Volume Fraction (%)	Diameter in (um)	Linearity			
	0-0.5	0.5-1.0	1.0-1.5	1.5-2.0			0-0.5 um	0.5-1 um	1-1.5 um	1.5-2 um
Hematite	0%	0%	0%	0%	70	0.005	LC	LC	LC	LC
Silicon	0-50%	50-92%	92-95%	95%	0.1	0.05	LI	LI	LI	LC
Gadolinium	0%	0%	0%	0%	0.1	0.05	LC	LC	LC	LC
Titanium Nitride	0%	0%	0%	0%	0.1	0.005	LC	LC	LC	LC

With the given concentrations of nanofluid and the particle size as can be seen in Table 4, only Si nanofluid has significant transmittance ranging from a lowest of 50% to a highest of 95% throughout the entire spectrum range of interest .

B. Transmittance for varying particle diameter

Table 5 shows results for a constant particle diameter of 5nm with the best overall performance offered by Gd followed by hematite. The maximum transmittance for Gd is 98.9% at a thickness of 1µm and volume fraction of 0.1% and that for hematite is 94% at a thickness of 0.1µm and a volume fraction of 50%. Silicon tends to offer a 95% transmittance between a wavelength range of 1-2 µm at a volume fraction of 5% and a fluid layer thickness of 1000µm which is a practicable dimension. The extremely high concentration of hematite makes it act like the solid conventional filters that are in use. TiN shows significant improvement in transmittance levels after 1.5µm.

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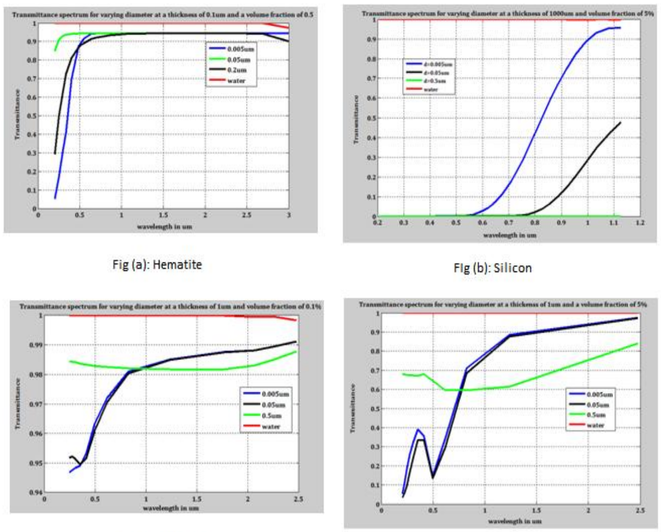

Fig (a): Hematite Fig (b): Silicon Fig (c): Gadolinium Fig (d): Titanium Nitride

Fig2: Showing the effect of varying particle diameter on transmittance for a. Hematite b. Silicon c. Gadolinium and d. Titanium Nitride.

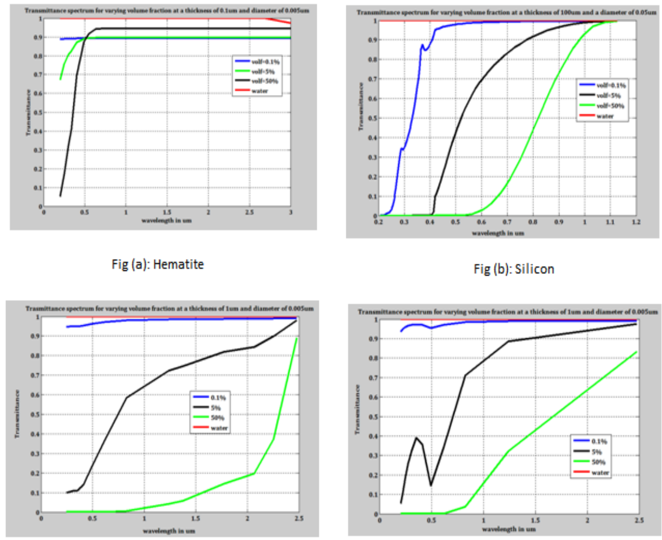

Fig (a): Hematite Fig (b): Silicon Fig(c): Gadolinium Fig (d): Titanium Nitride

Fig3: Showing the effect of varying volume fraction on transmittance for a. Hematite b. Silicon c. Gadolinium and d. Titanium Nitride.

Table 5

Nanofluid	Percentage Transmittance at different wavelengths at a diameter of 0.005um				Volume Fraction (%)	Thickness in (um)	Linearity			
	Wavelength (um)						0-0.5 um	0.5-1 um	1-1.5 um	1.5-2 um
	0-0.5	0.5-1.0	1.0-1.5	1.5-2.0						
Hematite	1-90%	90-94%	94%	94%	50	0.1	LI	LI	LC	LC
Silicon	0%	0-90%	90-95%	95%	5	1000	LC	LI	LI	LC
Gadolinium	0-96%	96-98.2%	98.2-98.5%	98.5-98.9%	0.1	1	LI	LI	LI	LI
Titanium Nitride	1-13%	13-78%	78-90%	90-92%	5	1	NI	LI	LI	LI

Table 6

Nanofluid	Percentage Transmittance at different wavelengths at a diameter of 0. 05µm				Volume Fraction (%)	Thickness in (µm)	Linearity			
	Wavelength (µm)						0-0.5 µm	0.5-1 µm	1-1.5 µm	1.5-2 µm
	0-0.5	0.5-1.0	1.0-1.5	1.5-2.0						
Hematite	0-95%	95%	95%	95%	50	0.1	LI	LC	LC	LC
Silicon	0%	0-30%	>30%	>50%	5	1000	LC	LI	LI	LI
Gadolinium	0-96%	96-98.2%	98.2-98.5%	98.5-98.9%	0.1	1	LI	LI	LI	LI
Titanium Nitride	1-13%	13-78%	78-90%	90-92%	5	1	NI	LI	LI	LI

It is visible from the figures as well as Table 6 that performance of all the nanofluids except Si shows a steady characteristic when compared to the values in Table 5. It can be assumed from the figures shown above that Si might reach a transmittance close to

95% at much higher wavelength ranges than have been provided here.

C. Transmittance for varying volume fraction

The following figures and tables show the effect of volume fraction on transmittance.

Table 7

Nanofluid	Percentage Transmittance at different wavelengths at a volume fraction of 0.1%				Diameter in (um)	Thickness in (um)	Linearity			
	Wavelength (um)						0-0.5 um	0.5-1 um	1-1.5 um	1.5-2 um
	0-0.5	0.5-1.0	1.0-1.5	1.5-2.0						
Hematite	90%	90%	90%	90%	0.005	0.1	LC	LC	LC	LC
Silicon	0-98%	98-100%	100%	100%	0.05	100	LI	LI	LC	LC
Gadolinium	95-97%	97-99%	99%	99%	0.005	1	LI	LI	LC	LC
Titanium Nitride	92-94%	94-99%	99%	99%	0.005	1	NI	LI	LC	LC

Table 7 shows that all the nanofluids have significantly high transmittance for the optical spectrum under consideration. Hematite has a steady transmittance rate at 90% throughout the spectrum. Si becomes steady at a 100% and Gd and TiN both reach a constant transmittance level at 99% at a wavelength of 1µm.

Table 8

Nanofluid	Percentage Transmittance at different wavelengths at a volume fraction of 5%				Diameter in (µm)	Thickness in (µm)	Linearity			
	Wavelength (µm)						0-0.5 µm	0.5-1 µm	1-1.5 µm	1.5-2 µm
	0-0.5	0.5-1.0	1.0-1.5	1.5-2.0						
Hematite	68-90%	90%	90%	90%	0.005	0.1	LI	LC	LC	LC
Silicon	0-40%	40-100%	100%	100%	0.05	100	LI	LI	LC	LC
Gadolinium	0-25%	25-65%	65-78%	78-82%	0.005	1	LI	LI	LI	LI
Titanium Nitride	1-15%	15-80%	80-90%	90-92%	0.005	1	NI	LI	LI	LI

It can be seen from Table 8 that transmittance at wavelengths below 0.5µm was greatly affected for all the nanofluids due to an increase in the concentration of nanoparticles in the base fluid. There is a considerable degradation of all values for Gd compared to those in Table 7. Both hematite and Si attains stability at 1µm.

Table 9

Nanofluid	Percentage Transmittance at different wavelengths at a volume fraction of 50% Wavelength (µm)				Diameter in (µm)	Thickness in (µm)	Linearity			
	0-0.5	0.5-1.0	1.0-1.5	1.5-2.0			0-0.5 µm	0.5-1 µm	1-1.5 µm	1.5-2 µm
Hematite	1-89%	89-95%	95%	95%	0.005	0.1	LI	LI	LC	LC
Silicon	0%	0-93%	93-100%	100%	0.05	100	LC	LI	LC	LC
Gadolinium	0%	0-1%	1-10%	10-20%	0.005	1	LC	LI	LI	LI
Titanium Nitride	0%	0-18%	18-42%	42-65%	0.005	1	LC	LI	LI	LI

Both Gd and TiN are affected the most with a further increase in the volume fraction of the nanoparticles reaching a highest at 20% and 65% transmittance respectively at 2µm. Hematite reached a steady transmittance of 95% at 1µm whereas the steady value for Si was 100% starting at 1.5µm.

IV. Conclusion

In general the main advantages of nanofluid optical filter are (a) it is suitable for selecting wavelengths in the ultraviolet, visible and infrared regions[8] (b) a single filter can be used for a range of central wavelengths, where the desired central wavelength region can be tuned by external magnetic field[8] (c) there is no need for changing the optical element for different wavelength regions[8] (d) tuning can be easily achieved by changing the field strength (e) the spectral distribution can be controlled by adjusting the polydispersity (objects that have an inconsistent size, shape and mass distribution) of the emulsion[8] (f) the intensity of the transmitted light can be controlled by changing the emulsion concentration[8] (g) it is simple to operate and less expensive compared to the existing filters[8]. This paper has not considered the effect of temperature and the influence of an external magnetic field on the transmittance spectrum of the nanofluid filters. Furthermore , in order for the simulation results to closely follow the practical outcome reflections at enclosure boundaries should be accounted for in a way explained in [7].

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